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AIR FORCE SYSTEMS COMMAND

INDUCTIVE ENERGY STORES

by

L. P. Poberezhskiy

FOREIGN TECHNOLOGY DIVISION

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INDUCTIVE ENERGY STORES

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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INDUCTIVE ENERGY STORES

L. P. Poberezhskiy.

In 1958 a report appeared in the press about the fact that in the USA pulsed wind tunnels had been put into operation which had very high parameters of the gas at the nozzle inlet (pressure up to 4000 atm and a temperature up to 20,000°K). This made it possible to obtain conditions in the working part which are close to those experienced by a body flying into the atmosphere with cosmic velocity. In the described pulsed wind tunnels the energy was accumulated in a capacitor bank or in an induction coil and was supplied to the gas by means of an electric discharge.

In the first version of a pulsed tunnel created in the gas-dynamics laboratory of AEDS an energy of 1 M J was stored in a capacitor bank with a voltage of 4 kilovolts. Increasing the stored energy makes it possible to increase the dimensions of the working part of the tunnel and of the studied model, to conduct the experiment for a longer period of time, to obtain greater densities of the gas flow and higher temperatures, and thereby to more closely approach flight conditions. Increasing the stored energy of the capacitors to 10 M J turned out to be a complex task. Therefore in the second version of the American pulsed wind tunnel an energy of 10 M J was stored in an induction coil. This made it possible to investigate models with a size on the order of 1 m.

During the development of an inductive store questions of a dual nature arise. First, during discharge of the store a power must develop which exceeds the power of the charging device otherwise the

use of a store loses sense. Second, the coil of the store must have a shape and dimensions which make possible its practical realization. Written below are some relationships which may make it possible to perform estimated calculations of an inductive store.

1. Discharge of the Store.

During discharge of the store the current decreases according to the exponential law

(1) $$i = I_0 e^{-\frac{r}{L}t} = I_0 e^{-pt}.$$

Here I_0 - current at the initial moment of dishcarge;

r - resistance of the discharge circuit.

It is understood that at the beginning of discharge the power source was shunted and that the resistance of the arc is significantly higher than the resistance of the coil wire and of the connecting wires, otherwise the efficiency of the store would be low.

The energy liberated during the discharge at moment t is expressed as

(2) $$W_t = \frac{I_0^2 L}{2}\left(1 - e^{-\frac{2r}{L}t}\right).$$

The first factor of the right part expresses the stored energy. Designating it W_0 we write the dimensionless relationship

(3) $$A = \frac{W_t}{W_0} = 1 - e^{-\frac{2r}{L}t}.$$

From this it is possible to determine the time during which the assigned part of the stored energy is liberated and the average discharge power with respect to time

(4) $$t \cdot \frac{L}{r} = \ln \frac{1}{1-A} = \varphi(A),$$

(5) $$P_{cp} = \frac{W_t}{t} = W_0 \frac{1 - e^{-2pt}}{t} = I_0^2 r \frac{A}{\varphi(A)} = I_0^2 r \Psi(A).$$

From (5) it is evident that for ensuring a high power it is necessary to provide a high arc resistance.

The function $\Psi(A)$, given in Fig. 1 characterizes the drop in power of the discharge due to a current drop. Its form shows that an increase in the discharge efficiency due to more complete use of the stored energy leads to a sharp drop in the average power.

The instantaneous power, developed during discharge is expressed as

$$P = I_0^2\left(1 - \frac{W_t}{W_0}\right) r. \tag{6}$$

From this it is evident that with actuation of 80% of the stored energy the power drops 5 times in comparison with the beginning of discharge and with actuation of 90%, 10 times.

Let us now calculate, as an example, what the resistance of the arc must be so that a store with a stored energy of 100 M J with a source current of 10 kA will develop an average power of 500 thousand kW with actuation of 80% of the stored energy. According to (5) and Fig. 1,

$$r = \frac{5 \cdot 10^8}{10^8} \cdot 2{,}04 = 10{,}2 \text{ ohms}$$

The question of the possibility of ensuring such a value of the arc resistance is unclear at the present time.

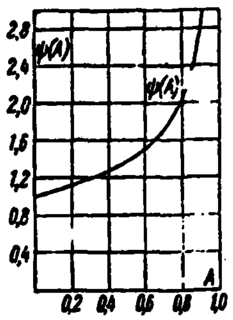


Fig. 1.

The arc resistance is nonlinearly dependent on the current, pressure in the chamber, electrode material, conditions of heat removal, etc.

The form of the volt-ampere characteristic depends on the rate of change of the current and voltage. In view of the great complexity of the elementary processes in an arc column, the value of arc resistance does not lend itself to calculation. In the development of new equipment one must either use existing experience or ensure the necessary arc resistance by various measures in the process of development of the installation. According to data existing in the literature it is possible to determine only the order of magnitude of the arc resistance. According to [3] with currents on the order of a kiloampere and at atmospheric pressure the arc resistance per unit of length of the column comprises thousandths of an ohm per centimeter. It is also known that the action of an air or water vortex on an arc, with unchanged current and pressure, may increase the arc resistance by an order [4], and increasing the pressure by 50-100 atm may increase it by another order [5]. When the arc is fed from a generator dynamo the arc length must be small due to the possibility of breakaway of the arc. Supplying power from an inductance coil should make it possible to achieve burning of arcs of greater length. Data is virtually absent on arc resistance with currents on the order of tens of kiloamperes, pressures on the order of hundreds of atmospheres and with great length. Therefore the question of arc resistance needs theoretical and experimental development.

Described below are methods for raising the power which are based on providing low arc resistance and a large current value.

Doubling, tripling, quadrupling, etc. of the charging current may be realized by switching sections of the coil with series connection to parallel connection. The operating principle of the circuit is clear from Fig. 2. During charging the form of the circuit is like that in Fig. 2a. Switches V3 and V2 are closed; switches V1 are open. When the charging process is finished switches V1 are switched on and each of the coils and the source are shorted. The source is disconnected by switch V2. A low-inductance reactor OP limits the current brought about by shorting of the source. Because of the low resistance of the coil wire and the shorts the expenditure of energy during the time necessary for switching is not great. After switch V2 is disconnected, switches V3 disconnect and coil currents begin to flow through the chamber where ignition of the arc

is initiated (for example, by introduction of a thin wire into the chamber).

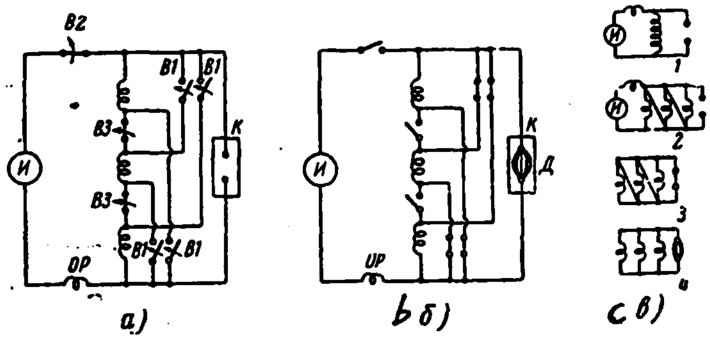


Fig. 2. Circuit with switching of sections: a and b - schematic diagrams; c - equivalent circuit: 1 - during charging; 2 - after connection of V1; 3 - after disconnection of V2; 4 - after disconnection of V3; I - source; K - chamber; D - arc.

Another method for increasing the current is the use of a transformer circuit. A secondary winding consisting of a small number of turns with low active resistance is wound onto the coil. The ends of this winding are connected to the discharge chamber. When the charging process ends and the power source, if this turns out to be necessary, is shunted and disconnected, the arc is initiated in the chamber (for example, by introduction of a wire, or by bringing together and separating contacts).

Let us examine the relationships characterizing the operation of a transformer store.

Let us introduce the following designations:

L_1 - inductance of the primary winding;

L_2 - inductance of the secondary winding;

r_1 - total active resistance of the primary circuit;

r_2 - active resistance of the secondary circuit (prevails over the arc resistance);

k - coefficient of transformation; $k = \frac{w_2}{w_1}$.

ω_1, ω_2 - numbers of turns of the primary and secondary windings;

i_1 - current in the primary circuit at a given moment of time;

i_2 - current in the secondary circuit at a given moment of time;

I_0 - current in the primary circuit before commutation;

Φ - total magnetic flux of both windings;

i_{10}, i_{20} - currents of the primary and secondary circuits immediately after commutation.

Of particular interest is the case when coupling coefficient between windings is equal to 1, i.e., when stray fluxes are absent.

This a practically important case because of the fact that in real coils a coupling coefficient is necessary which is close to 1. Early and Walker [2] obtained a coupling coefficient of 0.98 for a cylindrical coil.

The equations have the following form (see [6])

(7)
$$i_1 r_1 + \omega_1 \frac{d\Phi}{dt} = 0,$$
$$i_2 r_2 + \omega_2 \frac{d\Phi}{dt} = 0.$$

Let us use the relationships

(8)
$$\Phi = i_1 \frac{L_1}{\omega_1} + i_2 \frac{L_2}{\omega_2},$$

(9)
$$\frac{L_2}{L_1} = k^2$$

the initial condition for (7)

(10)
$$L_1 I_{10} = L_1 i_{10} + L_2 i_{20} \cdot \frac{1}{k}.$$

Solving the equations we obtain the following relationships

(11)
$$i_1 = I_0 \frac{r_2}{r_2 + r_1 k^2} e^{-pt} = i_{10} e^{-pt},$$

(12)
$$i_2 = I_0 \frac{r_1 k}{r_2 + r_1 k^2} e^{-pt} = i_{20} e^{-pt},$$

(13)
$$p = \frac{r_1}{\left(1 + \frac{r_1}{r_2} k^2\right) L}.$$

From equation (13) it is evident that in the transformer circuit with unchanged resistance of the primary circuit the rate of discharge

does not increase in comparison with a conventional circuit inasmuch as the value of the attenuation coefficient for the transformer circuit is not greater than the analogous value for a conventional circuit. Thus, the use of a transformer circuit with unchanged parameters of the primary circuit does not increase the power of the discharge. It is possible, however, following ignition of the arc in the secondary winding, to introduce a supplementary resistance $r_{1\partial}$ into the circuit of the primary winding. In this case the current of the primary circuit will fall and the current of the secondary circuit will rise. The discharge process will be accelerated and the power will increase.

The expression for the ratio of values of the liberated energy in the primary and secondary windings is written as

(14) $$\eta = \frac{\int_0^\infty i_{20}^2 r_2 e^{-2pt}\, dt}{\int_0^\infty i_{10}^2 r_1 e^{-2pt}\, dt}.$$

Using expressions (11) and (12) we obtain

(15) $$\eta = \frac{r_1 k^2}{r_2}.$$

Now let us write the expression for the maximum voltage on $r_{1\partial}$ $(r_{1\partial} \gg r_1)$

(16) $$U_1 = i_{10} r_{1\partial}.$$

Having used (11), we express $r_{1\partial}$

(17) $$r_{1\partial} = \frac{U_1 (r_2 + r_{1\partial} k^2)}{I_0 r_2}.$$

Let us express $r_{1\partial} k^2$ from (15) and substitute the obtained expressions in (13). Following transformations we have

(18) $$p = \frac{U_1}{L_1 I_0}.$$

The value of the attenuation coefficient enables us to obtain an expression for power, using (5). Let 80% of the stored energy be actuated. Then

$$(19)\qquad 1-e^{-2pt}=0{,}8,\quad 2pt=1{,}6,\quad t=\frac{0{,}8}{p}.$$

Using (18) and (19) we write

$$(20)\qquad P_{cp}=\frac{0{,}8\,W_0}{t}=W_0\,\frac{U_1}{L_1I_0}=\frac{U_1I_0}{2}.$$

This expression shows that if the charging current and the increase in voltage on the terminals of the primary winding are given, then the power developed by the inductive store of the transformer type may be ensured with any resistance of the arc. This is explained by the fact that, as can be seen from (12), the less the resistance of the arc, the greater the current flowing through it.

The value of the coefficient of energy use in the secondary winding η in principle can be made quite high. This is evident from the fact that eight independent variables enter into the system of equations (13), (15), (17):

$$U_1,\ I_0,\ L_1,\ r_2,\ r_{1\partial},\ k,\ \eta,\ p.$$

Existing equipment determines the values U_1, I_0, L_1, properties of the arc determine the value r_2. If we assign value η. then for $r_{1\partial}$ and k certain conditions will be imposed. Inasmuch as these values may be varied the imposed conditions may be satisfied.

Let us return to the example examined above. With a source current of 10 kA and a desired average power of 500 thousand kW the increase in voltage must be

$$U_1=\frac{2P_{cp}}{I_\partial}=50\ \mathrm{kV}$$

Let the arc resistance be $0.5\cdot10^{-2}$ ohms, the desired coefficient $\eta=10$. Then the value of resistance $r_{1\partial}$ is

$$r_{1\partial}=\frac{U_1(1+\eta)}{I_0}=\frac{50\cdot10^3\cdot11}{10^4}=55\ \text{ohms}$$

The transformation coefficient must be equal to

$$k=\sqrt{\frac{\eta r_2}{r_1}}=\sqrt{\frac{10\cdot0{,}5\cdot10^{-2}}{55}}=\frac{3}{100}.$$

Let us note, however, that up until now we have examined a transformer circuit in the absence of stray fluxes. These fluxes, as was mentioned, are small; they apparently have an insignificant effect on the distribution of the energy being liberated between the primary and secondary windings. However, in view of the presence of flux linkage of leakage the current of the primary winding may not change instantaneously. This brings about very high, although short-term, overvoltages on the resistance introduced into the primary circuit. In the examined example these overvoltages would be 10 kA x 55 ohm = 550 kV.

We may point out several ways to eliminate or decrease these overvoltages.

1. Application of nonlinear resistance $r_{1\partial}$.

2. Sectioning of $r_{1\partial}$ and introduction of it in parts.

3. Selection of conditions with which the value of the resistance is small. From the expression for $r_{1\partial}$ it is evident that a reduction of this value will bring with it, with unchanged U_1, a reduction of η. If we permit low values of η, then the overvoltages caused by stray fluxes will be low.

2. Inductance Coils.

From the expression for stored energy and also from the relationship between the resistance of the coil r charged by current and the power of the source P_u it is possible to obtain the following relationship

$$(21)\qquad \frac{2W_0}{P_u} = \frac{L}{r} = \tau,$$

Which shows that with a given power of the source, the stored energy is greater the higher the time constant of the coil. The object to be examined will be a cylindrical coil of rectangular cross section without an iron core. The time constant of such a coil may be expressed by a linear dimension, for example height a, geometric parameters Υ and α (see Fig. 3) and the specific resistance of the coil wire.

Actually, if we use the relationship $w = \frac{\gamma a^2}{d_n}$,

d_n - diameter of the wire, then according to [7]

$$L = \frac{\mu_0}{4\pi} w^2 d \Phi = \varphi_L (\alpha, \gamma) \frac{a^5}{d_n^4}, \qquad (22)$$

where d - average diameter of the coil;

Φ - a certain function of α and γ;

w - the number of turns.

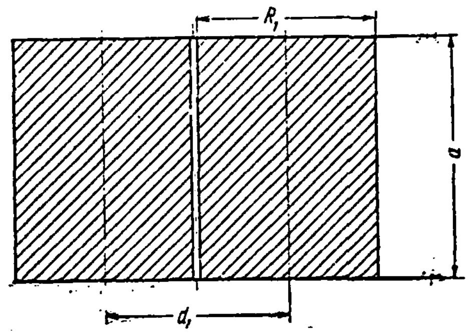


Fig. 3. Form of the inductance coil.

The expression for the active resistance may be written as

$$r = \rho \frac{\pi d w}{d_n^2} = \varphi_r (\alpha, \gamma) \frac{a^3}{d_n^4} \cdot \rho. \qquad (23)$$

Here ρ - specific resistance of the coil wire;

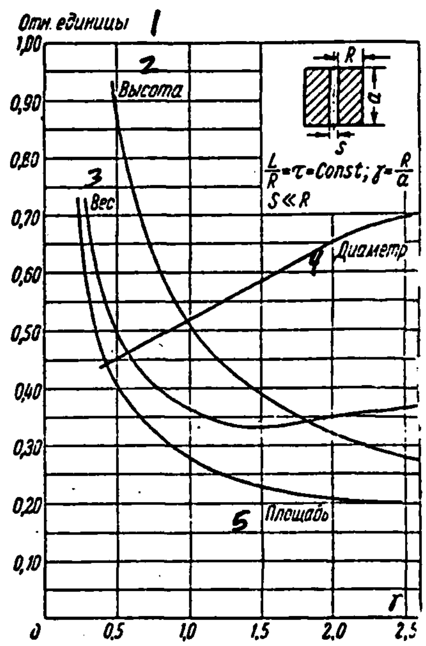
φ_r - a certain function of α and γ, i.e. of the form of the coil.

From the expressions for L and r we obtain

$$\tau = \frac{L}{r} = \varphi (\alpha, \gamma) \frac{a^2}{\rho}. \qquad (24)$$

It is possible to investigate the effect of the shape on the dimensions and weight of a coil with an assigned time constant. Fig. 4 shows the effect of extension of the coil in the direction of height, i.e. of the ratio of the height to the thickness of the winding.

From the figure it is evident that the least weight with a given time constant is possessed by a coil with a ratio of the winding thickness to the height of 1.5 and that the weight of the winding is ineffectively used in high coils. Fig. 5 shows the effect of filling of the cross section, i.e., of the ratio of the winding thickness to the average diameter with a ratio of the external diameter to the height equal to 1. It is evident that an increase in the filling has little effect on the weight of the coil but yields a gain in dimensions.



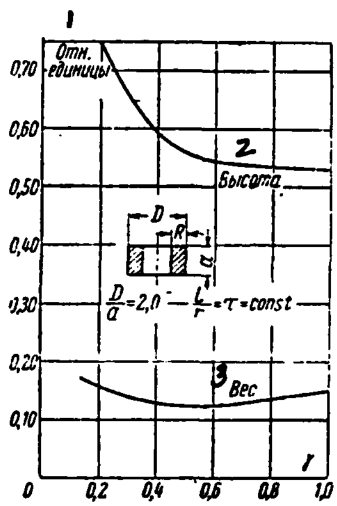


Fig. 4. Effect of the height of the coil on the dimensions and weight. KEY: 1. relative units. 2. height. 3. weight. 4. diameter. 5. area.

Fig. 5. Effect of the filling of the cross section of the coil on the dimensions and weight. KEY: 1. relative units. 2. height. 3. weight.

As an example, let us now determine the dimensions of a coil in which 100 M J are stored with a source power of 10 thousand kW. The value of the constant $\varphi(a, \gamma)$ for a coil, the shape of which is close to optimum (coil, Fig. 3), comprises $0.6 \cdot 10^{-7}$ [7]. If the material

of the coil is aluminum

$$a=\sqrt{\frac{2\cdot10^{8}\cdot3,2\cdot10^{-8}}{10^{7}\cdot0,6\cdot10^{-7}}}=3,3\ \mathrm{m}$$

Thus, the height of the coil is 3.3 m, and the outside diameter, 4.95 m.

Up until now there has been no examination of the problem of the value of induction of the magnetic field in the space near the coil. Meanwhile, at a distance of 2-3 m from a coil storing an energy of 100 M J, induction may reach a value of 800-900 G. If it is not possible to place metal objects a sufficient distance away then the external field of the coil must be reduced to a value on the order of units of gauss, which may be achieved in various ways (see, for example, author's certificate No. 142791).

Let us pause for a moment on how we may calculate the induction of the external magnetic field of a solenoid of rectangular cross section. For an infinitely thin turn or a coil of w turns we may write the following expression for induction in a random point of space [8]

$$B_{l}=\frac{\mu_0 Iw}{2\pi l}\cdot\frac{m}{[(n+1)^2+m^2]^{1/2}}\left[-K+\frac{m^2+1+n^2}{(n-1)^2+m^2}\,E\right],$$

$$B_{z}=\frac{\mu_0 Iw}{2\pi l}\cdot\frac{m}{[(n+1)^2+m^2]^{1/2}}\left[K+\frac{n^2-1-m^2}{(n-1)^2+m^2}\,E\right],$$

$$\beta=\arcsin\sqrt{\frac{4n}{(n+1)^2+m^2}},$$

$$m=\frac{z}{l},\quad n=\frac{g}{l}.$$

Here z and l - coordinates of a point in the cylindrical system;

g - radius of a turn;

K and E - complete elliptical integrals of argument β.

These formulas may also be used for calculating the field of a solenoid with a finite size of the cross section under the condition of division of the area of the cross section into sufficiently small parts. Calculations show that during the computation of the field in the plane of symmetry at a distance on the order of the radius of

the coil, division of the solenoid into two or eight parts gives a difference in the value of induction of 20%; division into eight or thirty-two parts gives a difference of 2-3%. Thus, division into eight parts ensures sufficient accuracy of the calculations.

The question of the maximum permissible value of induction of the external magnetic field is unclear. This question must be examined both from the viewpoint of the harmful effect of magnetic fields and from the viewpoint of losses connected with eddy currents induced in metal objects during discharge of the store. We must find optimum configurations of an air coil in a plane and the optimum shape of its cross section. The problem of mechanical forces must be examined. A very important problem is that of insulating the coil. And finally, the possibility is not excluded that in some case the use of ferromagnetic materials could be beneficial.

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